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Kilopower Space Reactor Launch Safety
Maximum Credible Dose for a Criticality Accident

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Introduction

This note examines potential consequences for the Kilopower small space reactor going critical during a launch accident. The goal of this analysis is to postulate the dose at a distance that could be generated during a criticality accident event (with emphasis on potential public doses.) This note does not examine local consequences to an individual who would be close enough to the reactor (within several 10's of meters) to receive a lethal dose from the direct shine of neutrons and gamma radiation present when the reactor is critical.

Scenario Description

The reactor fault conditions leading to a criticality have been postulated by several previous space reactor studies (for an example, see Weitzburg[1].) From these studies, the most likely generic scenarios for a space reactor going critical during a launch involves the following potential issues:

1. The reactor being surrounded by a medium (such as water or wet sand) that increases moderation or reflection causing a criticality, or
2. The reactor core is deformed into a more favorable geometry causing criticality, or
3. The control mechanism being separated from the reactor by a blast or fire causing an insertion of reactivity, or
4. Some combination of these events.

One base assumption for scenario No. 1 involving the reactor surrounded by water is that the reactor survives the launch accident mostly intact and that the reactor falls onto land near water (say on a beach) such that the reactor is not always complete submerged, but instead is partially cover by the incoming tides. This is important since a reactor that is completely submerged in water may be critical but will not adversely impact the public given that any radiation will not be airborne but instead will be dispersed into the ocean.

Reactor criticality accident typically are either a short-term accidents or long-term accidents. A short-term accident is one where the reactor has a step insertion of reactivity (initial burst) and the reactor self disassembles given the thermal shock. These accidents are on the order of milliseconds in length. A long-term accident is one where the reactor has an initial burst and survives the burst, followed by a longer period with the reactor critical or pulsing critical. Long-term events can last days. The base cases for criticality events will be divided into two base cases, short-term and long-term events as follows:

Base Case 1. Short-term: Reactor has a step insertion of reactivity (initial burst) and the reactor self disassembles given the thermal shock. This event could be caused by:

- The control rod being ejected by a blast from a rocket explosion
- The control rod being ejected by impact with water or land
- The reactor is deformed into a geometry favorable for criticality, but self-destructs by initial burst.
- The reactor is immersed in water is further moderated or reflected and self-destructs by initial burst.

Base Case 2. Long-Term: Reactor has an initial burst followed by a longer period with the reactor critical or pulsing critical. This event could be caused by:

- Reactor survives the initial burst and settle into an equilibrium at temperature that keeps the k_{eff} at equilibrium. This might be the situation for a deformed reactor on land.
- Reactor survives the burst and the reactor pulses (critical and non-critical) as water moves in and out of the reactor. This could be the situation where the reactor lands on the shore and the tide comes in and out covering the reactor with water or the reactor is boiling away water fast enough to cause a pulsing effect.

Fission Yields Assigned to for KiloPower

The fissions yields assigned to critical accidents come from McClure 2018[2] and are based on known criticality accidents. These values are viewed as the "maximum credible" values for a criticality accident. The data is taken from McLaughlin's[3] review of all know criticality accidents worldwide to date. It is believed to be a complete list, since no new criticality events have occurred since the document was produced. Criticality accidents are binned into Bar/Dry Solid and Moderated/reflected systems using McLaughlin classification of accidents. In addition, the accidents are binned by Case 1 - Initial burst (short term) or by Case 2 - initial burst followed by long term critical (long term). This forms four total cases for examination. Each accident is assigned a value that is equivalent to the maximum values in found in McLaughlin's data. The fission yields are presented in Table 1.

Table 1. Fission Yields Assigned to KiloPower

Case	Description	Bin	Initial burst yield	Total fission yield
1a	Short term - Step insertion by rod ejection or geometry change	Bare/Dry Solid	5E+17	
1b	Short term - Step insertion by water immersion	Moderated/reflected system	5E+18	
2a	Long term - Initial burst followed by longer critical period caused by geometry change or partial rod withdrawal	Bare/Dry Solid	5E+17	1E+19* * 6-day excursion
2b	Long Term - Initial burst followed by longer term pulsing reactor from water ingress	Moderated/reflected system	5E+18	1E+20* * Long term excursion

Release Fractions for Accident Cases

The release fractions will change for each specific accident case. The two main issues are 1) the amount of fuel damage (associated with a short-term step insertion that destroys the core versus a long-term accident where core is intact) and 2) the presence of water. These issues are related to the four cases presented in Table 1. The short-term accidents are associated with massive fuel damage from a burst event leading to core destruction. The long term-events are associated with minimal fuel damage. Non-water events will be associated with dry/bare systems. Water events will be associated with moderated/reflected systems. The release fractions are then discussed for each accident case below.

Case 1a – Short-term step insertion leading to reactor damage with no water present

A reactor that has undergoes a step insertion of reactivity large enough to self-destruct and shutdown the reactor will also have a significant amount of fuel damage. The destruction of the reactor is cause by a thermal shock-wave traveling through the reactor as portions of the fuel either melt or vaporize. This leads to structural cracking/destruction of the reactor core internals and fuel with a portion of the reactor being ejected outward. Examples of such tests are the SNAPTRAN-2 test and KIWI-TNT test performed in the 1960s.

The SNAPTRAN-2 destructive test was a $5 insertion of reactivity to the SNAP-10A reactor, (a small space reactor), by artificially turning all the control drums at a high speed. No water was present during the test. The destruction to the core is described as follows from Johnson 1966[4]:

> *Pieces of beryllium reflector, varying from fragments to 1 x 2 inches in size were found within the 100-meter arc. Beryllium shim fragments were also found in a direct line from the respective drum positions. Fuel fragments were found throughout the area with sizes ranging from minute particles to approximately 3/4 inches. These larger fuel fragments were found at distances up to 100 meters. The smaller fuel fragments were retained within the 10- to 15-meter arc. Pieces of fuel element cladding were also found within the 15-meter arc, all of which were severely mangled. The upper grid plate was found approximately 20 meters from the reactor. The drum shafts which were not visible during the TV survey were found, severely damaged, on the test cell floor beside the test dolly.*

Cordes 1967[5] states that for radiological releases of SNAPTRAN-2

> "*the SNAPTRAN-2 test, 75 percent of the noble gases, 70 percent of the halogens, 45 percent of the tellurium, and 4 percent of the remaining solids were released.*"

The KIWI-TNT destructive test was a ~$8 insertion of reactivity to the Kiwi reactor, (a thermal nuclear rocket), by artificially turning all the control drums at a high speed. This produced a 3E20 fission event in the reactor that caused an explosion approximately the same as 100 to 150 lbs of TNT equivalent. The reactor core was completely destroyed. From Fultyn 1968[6] the radiological releases were as follows:

> *From 5 to 20% of the reactor core was vaporized, with approximately 67% of the products from about 3 X 10^{20} fissions released to the effluent cloud. Radiation effects from the cloud passage were less than predicted in the pretest safety evaluation report.*

Later in the report it is clear that most of the fission products were Xenon, Iodine and Tellurium. Small amounts of Lanthanum, Ruthenium and Barium were also found. This would indicate some agreement with the values measured for SNAPTRAN-2.

For step insertion accidents for Bare/Dry solids (no water), Base Case 1a, the release fractions will be assigned using the values from SNAPTRAN-2. The alkali metals (Cesium) will be assigned the same release fraction as the Halogens (Iodine). Using the grouping of chemical classes from Restrepo 1991[7], the follow release fractions are assigned.

Table 2. Release Fraction for Case 1a, Step Insertion – Bare/Dry Metal (Based on SNAPTRAN-2)

Group No.	Group Name	Rep. Ele.	Elements in Group	ARF
1	Noble Gases	Xe	Xe, Kr, He, Ne, Ar, Rn, H	7.5E-1
2	Alkali Metals	Cs	Cs, Rb, Li, K, Fr, Na	7E-1
3	Alkali Earths	Ba	Ba, Sr, Mg, Ca, Ra, Be	4E-2
4	Halogens	I	I, F, Cl, Br, At	7e-1
5	Chalogens	Te	Te, S, Se, O, Po, N	4.5E-1
6	Platinoids	Ru	Ru, Rh, Pd, Os, Ir, Pt, Au, Ni	4E-2
7	Transition Metals	Mo	Mo, V, Cr, Fe, Co, Mn, Nb, Tc	4E-2
8	Tetravalent	Ce	Ce, Ti, Zr, Hf, Th, Pa, U, Np Pu	4E-2
9	Trivalent	La	La, Al, Sc, Y, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Bk, Cf	4E-2
10	Main Group I	Cd	Cd, Hg, Zn, As, Sb, Pd, Tl, Bi	4E-2
11	Main Group II	Sn	Sn, Ca, In, Ag	4E-2
12	Boron	B	B, Si, P, C	4E-2

Case 1b – Short Term step insertion by water immersion with fuel damage

The SNAPTRAN-3 test was, much like the SNAPTRAN-2 test, an experiment to examine reactivity insertion in a small space reactor, SNAP-10A. This test was a reactivity insertion caused by immersing the reactor in water. The SNAP reactor was super critical in water and in the SNAPTRAN-3 test, water caused the reactor to be ~3.60 dollars in excess above delayed critical. This caused an initial burst of 1.2E18 fissions. The reactor damage, as described in the summary section of the test report[8] was as follows:

> *The resulting power transient caused the core vessel to blow apart and the core to be disassembled. All 37 fuel-moderator elements were either destroyed or severely damaged. All six in-core beryllium filler pieces were broken in approximate halves at the reactor center-plane. A plume of water from the test tank was raised to a height of approximately 40 ft.*

Fission product release was very low for this experiment because the water scrubbed a good portion of the fission products that were released. Cordes[9] estimated that 99% of the fission products were retained by the water. Iodine (a Halogen) was not detected in the release plume. Only the noble gases (and their daughter products) were detected in the plume. It is estimated that 3% of the noble gases were released.

For this analysis it will be assumed that 3% of the noble gases are released based upon the SNAPTRAN-3 results. For the more volatile groups of Cs (alkali metals) and I (halogens) the release fraction will be set to 5E-3 (0.5%) for conservatism. This value was chosen because it is an order of magnitude less than the values for heated spent fuel from Restrepo 1991. These values are given in Table 3.

Table 3. Release Fraction for Case 1b, Step Insertion – Water Immersion (Based on SNAPTRAN-3)

Group No.	Group Name	Rep. Ele.	Elements in Group	ARF
1	Noble Gases	Xe	Xe, Kr, He, Ne, Ar, Rn, H	3E-2
2	Alkali Metals	Cs	Cs, Rb, Li, K, Fr, Na	5E-3
3	Alkali Earths	Ba	Ba, Sr, Mg, Ca, Ra, Be	0
4	Halogens	I	I, F, Cl, Br, At	5E-3
5	Chalogens	Te	Te, S, Se, O, Po, N	0
6	Platinoids	Ru	Ru, Rh, Pd, Os, Ir, Pt, Au, Ni	0
7	Transition Metals	Mo	Mo, V, Cr, Fe, Co, Mn, Nb, Tc	0
8	Tetravalent	Ce	Ce, Ti, Zr, Hf, Th, Pa, U, Np Pu	0
9	Trivalent	La	La, Al, Sc, Y, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Bk, Cf	0
10	Main Group I	Cd	Cd, Hg, Zn, As, Sb, Pd, Tl, Bi	0
11	Main Group II	Sn	Sn, Ca, In, Ag	0
12	Boron	B	B, Si, P, C	0

Case 2a – Long-term accident, initial burst followed by longer critical period with no fuel damage and no water present.

For Case 2a, Initial burst followed by longer critical period caused by geometry change or partial rod withdrawal, the main assumption is the reactor remains "relatively" intact. Meaning the fuel is still in a geometry very close to the original. This means the initial burst was not strong enough to break or melt the reactor. For these releases, both the DOE Handbook[10] on release fractions and the NRC Handbook[11] on Fuel Cycle facilities analysis recommend the work of Restrepo 1991 as the basis for release fractions. These values should be representative of an intact reactor releasing fission products and are shown in Table 4.

Table 4. Release Fractions for Case 2a, Long Critical Period, No Water (Based on Heated Spent Fuel - Restrepo, 1991)

Group No.	Group Name	Rep. Ele.	Elements in Group	ARF
1	Noble Gases	Xe	Xe, Kr, He, Ne, Ar, Rn, H	5E-1
2	Alkali Metals	Cs	Cs, Rb, Li, K, Fr, Na	2E-1
3	Alkali Earths	Ba	Ba, Sr, Mg, Ca, Ra, Be	3E-2
4	Halogens	I	I, F, Cl, Br, At	5E-2
5	Chalogens	Te	Te, S, Se, O, Po, N	7E-2
6	Platinoids	Ru	Ru, Rh, Pd, Os, Ir, Pt, Au, Ni	2E-3
7	Transition Metals	Mo	Mo, V, Cr, Fe, Co, Mn, Nb, Tc	3E-2
8	Tetravalent	Ce	Ce, Ti, Zr, Hf, Th, Pa, U, Np Pu	4E-4
9	Trivalent	La	La, Al, Sc, Y, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Bk, Cf	6E-4
10	Main Group I	Cd	Cd, Hg, Zn, As, Sb, Pd, Tl, Bi	4E-3
11	Main Group II	Sn	Sn, Ca, In, Ag	4E-3
12	Boron	B	B, Si, P, C	6E-4

Case 2b – Long-term accident, initial burst followed by longer critical period but reactor is in water during critical periods

For Case 2B, Initial burst followed by longer critical period caused by water immersion, the main assumption is again that the reactor remains “relatively” intact. Meaning the fuel is still in a geometry very close to the original. This means the initial burst was not strong enough to break or melt the reactor. However, unlike Case 1a, the reactor will be covered by water when it is critical (say by tides coming in and out.) This means that much like Case 1b, the fission products will be scrubbed heavily by the water when it is present. The scenario again is one where the reactor survives the launch accident mostly intact and that the reactor falls onto land near water (say on a beach) such that the reactor is not always complete submerged, but instead is partially cover by the incoming tides. Therefore, it must also be assumed that some fission product release occurs while the reactor is sub-critical, (i.e. fuel is hot enough to release fission products.) This means the release will be somewhere between Cases 1b and Case 2a. For this case, the Restrepo 1991 values for heated spent fuel will be divided by 10 as an approximation. This assumption is somewhat arbitrary, but it also brings the release of the noble gases more in line with values seen in Case 1b, for a reactor that burst and is destroyed by covered by water. These values are presented in Table 5.

Table 5. Release Fractions for Case 2b, Long Critical Period - Water (Based on Heated Spent Fuel Divided by 10 - Restrepo, 1991)

Group No.	Group Name	Rep. Ele.	Elements in Group	ARF
1	Noble Gases	Xe	Xe, Kr, He, Ne, Ar, Rn, H	5E-2
2	Alkali Metals	Cs	Cs, Rb, Li, K, Fr, Na	2E-2
3	Alkali Earths	Ba	Ba, Sr, Mg, Ca, Ra, Be	3E-3
4	Halogens	I	I, F, Cl, Br, At	5E-3
5	Chalogens	Te	Te, S, Se, O, Po, N	7E-3
6	Platinoids	Ru	Ru, Rh, Pd, Os, Ir, Pt, Au, Ni	2E-4
7	Transition Metals	Mo	Mo, V, Cr, Fe, Co, Mn, Nb, Tc	3E-3
8	Tetravalent	Ce	Ce, Ti, Zr, Hf, Th, Pa, U, Np Pu	4E-5
9	Trivalent	La	La, Al, Sc, Y, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Bk, Cf	6E-5
10	Main Group I	Cd	Cd, Hg, Zn, As, Sb, Pd, Tl, Bi	4E-5
11	Main Group II	Sn	Sn, Ca, In, Ag	4E-5
12	Boron	B	B, Si, P, C	6E-5

Summary Closing Thoughts on Release Fractions

The worst-case release fractions is Case 1a, where the prompt burst destroys the reactor with no water present. However, this case will also be paired with the lowest number of fissions.

For two cases with water Case 1b and 2b, the release will be highly mitigated by the water. A case not explicitly shown is the case of a reactor falling into the ocean. For this case, the water cover will be enough to make the atmospheric releases essentially zero. This can be shown by the historical use of water as a fission product scrubber to reduce releases in light water reactors. Pressurized water reactors use containment sprays to reduce fission product releases. Boiling water reactors can scrub fission product using the reactor suppression pool.

Longer-term releases will have a high number of fissions, but the intact reactor has lower release fractions and this will mitigate the dose.

CONSEQUENCE CALCULATIONS

To calculate the dose, two receptor locations were chosen. The first is 1000 m and the second is 100 m. These values have some precedent in the DOE community. 1000 m is a typical value for public standoff. 100 m is used as the distance for a nearby worker. The standard formulas for dose and accident source term (as presented in DOE-HNBK-3010[10]) are shown below for inhalation (note dose from radioactive shine is ignored for this calculation, but it's total contribution will be smaller than from inhalation.)

$$\text{Dose} = X/Q \times BR \times SA \times DCF \times ST \qquad \text{[Eq. 1]}$$

$$\text{Source Term (ST)} = MAR \times ARF \times RF \times DR \times LPF \qquad \text{[Eq. 2]}$$

Combining the equations provides:

$$\text{Dose} = MAR \times ARF \times RF \times DR \times LPF \times X/Q \times BR \times SA \times DCF \qquad \text{[Eq. 3]}$$

Where,

MAR = Material at risk (Curie inventory of radioactivity in the core)
ARF = Airborne release fraction
RF = Respirable fraction
DR = Damage Ratio (assumed to be 1)
LPF = Leak Path Factor (assumed to be 1)
X/Q = Atmospheric dispersion factor (s/m^3)
Br = Breathing rate (m^3/s)
SA = Specific activity (set to 1, since MAR is in curies not grams)
DCF = Dose Conversion Factor (Rem/Ci)
Dose = Total Effective Dose Equivalent (50 yr) in Rem

The MAR is the radioactivity in the reactor core based on the number of fissions for the accident assumed from Table 1. All fission products for which ICRP has a DCF are included in the MAR. The fission product inventory is calculated by the Los Alamos National Computer code CINDER and Monteburns based upon the burn up of U^{235} from the criticality accident and the reactor cross-section. This means that the MAR is reactor specific and is calculated using the Kilopower design.

Given that the distance to the two receptors is 100 m and 1000 m, the travel time of the plume (about 1 min for 100 m, to several min for 1000 m) is used as the delay time after the accident for the "at the receptor" inventory.

All releases are assumed to be instantaneous. This is a good assumption for burst releases, but is conservative for long-term releases. In the calculations, the receptor is present for the duration of the plume passage.

All releases are assumed to be ground level releases with the receptor at the plume centerline. Ground level releases will produce higher (conservative) doses relative to the elevated releases say from fires and explosions, because lofting of the plume causes more dispersion. The centerline dose is the highest does, with dose away from the centerline being smaller.

Using equation 3, the dose for each individual isotope was calculated in a spreadsheet. The values are then summed over all fission products to arrive at the total dose to the 1000 m and the 100 m receptor.

The other information needed for calculating dose is provided in Table 6. The table presents the parameters such as breathing rate, atmospheric dispersion coefficients, dose conversion factors used to calculate a dose value.

Table 6 - Assumed Values for Dose Calculations

Parameter	Symbol	Value	Reference
Atmospheric dispersion factor for the 1000 m receptor	X/Q_{1000}	1.E-4 s/m^3	Based upon mid-point value, Figure A-3 from Napier[12], see discussion below.
Atmospheric dispersion factor for the receptor at 100 m	X/Q_{100}	3.5E-3 s/m^3	DOE-STD-1189-08[13], pg. A-4
Breathing rate	BR	3.3E-4 m^3/s	SBT-14BE-32792 and NNSA Supplemental Guidance[14]
Release Fraction (Airborne Release Fraction times Respirable Fraction)	ARF x RF	Varies by chemical class	Provided in Tables 2 to 5 in this document
Damage ratio	DR	1	DOE-STD-3009-94[10]
Leak path factor	LPF	1	DOE-STD-3009-94[10]
Dose conversion factor for 1000 m, adult, absorption is fast, 1 micron particle size	DCF_{Pub_m}	Varies by Isotope (Sv/Bq)	ICRP-72[15]
Dose conversion factor for 100 m, adult, 5 micron particle size	DCF_{cw_m}	Varies by Isotope (Sv/Bq)	ICRP-68[16]

* The conversion of Sv/Bq to rem/Ci is as follows: 1 Sv = 100 rem, 1 Ci = 37,000,000,000 Bq

The atmospheric dispersion coefficient for the public was estimated from Napier[12], for a ground level releases and a wind speed of 1 m/s. A ground level release is chosen, since a reactor falling from a launch accident will strike the ground or ocean and then release is assumed to occur with minimal height increase over that of level ground. This is a conservative assumption. A wind speed of 1 m/s is also very conservative and rarely occurs in nature, except for very stable conditions (like stability class D or F) during very cold months. It is chosen for conservatism. The atmospheric dispersion coefficient plot was taken from Figure A-3 Napier[12] and is reprinted as Figure 1.

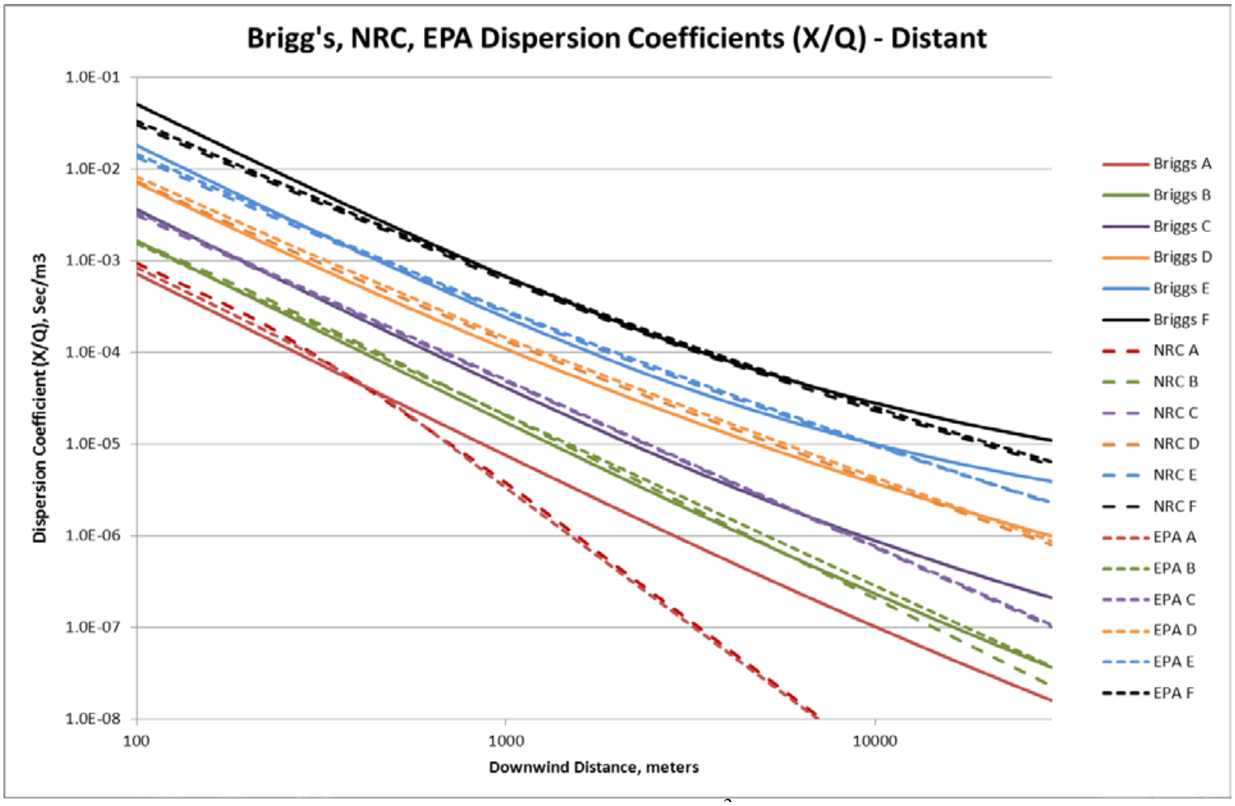

Figure 1. – Reprint, Atmospheric Dispersion for a Ground Level Release, Wind Speed = 1m/s

Results

The dose for 100 m and 1000 m receptors are presented in Table 7. The dose provides insights into the potential doses from criticality events from a space reactor. First the doses at 100 m are in the 10s of millirem to 100s of millirem for that receptor. The doses for the 1000 m receptor are in the sub millirem to single digit millirem range. These results are consistent with other calculations for these types of events for DOE nuclear facilities with similar numbers of fissions[17].

The experimental results from the SNAPTRAN program and Kiwi program did not see significant doses downwind either. A summary of the SNAPTRAN test radiological impacts[6] states that:

> *The SNAPTRAN-2 test confirmed the results of the SNAPTRAN-3 test that a reactivity accident with a "virgin fueled" SNAP 10A/2 reactor does not pose any undue hazard to the general public. The total integrated radiation exposure dose at the NRTS site boundary (10^4 meters) was less than 10 mR for both tests. Likewise, the spread of contamination was limited to a radius of 200 meters from the reactor following both tests.*

Summary tables for the SNAPTRAN test have doses less than a rem at 100 m and in the millirem in the 1000 m range. A summary of the Kiwi TNT test radiological impacts[6] states that:

> *From 750 to approximately 2,000 ft downwind, little, if any, injury or clinical effects would occur, but exposures would exceed 3 rads and would require administrative investigation and reporting. Beyond approximately 1.5 mile, doses even in the path of the cloud would be below a few hundred millirad, and should present no problems.*

Note, the difference between the rad and rem is that rad is a measurement of the radiation absorbed by the material or tissue and rem is a measurement of the biological effect of that absorbed radiation. For this study, rad and rem may be considered equivalent. In addition, Kiwi-TNT was a much large number of fissions than the SNAPTRAN test and higher than the number of fissions used for Case 1a by three orders of magnitude. So, doses will be higher for Kiwi-TNT than SNAPTRAN or this study.

The doses are very about the same order of magnitude of dose calculations for explosions and fires for Kilopower[18]. However, the fire and explosion calculations were very conservative since the release fractions were for an entirely aerosolized reactor core, not just a damage core as in these calculations. Fires and explosions do compensate by have a very small source term.

Finally, the difference between the presence of water is clearly seen in the results between cases 1a and 2a versus cases 1b and 2b. Case 1a shows the impact of a completed destructed reactor core without water present. This accident would be the worst-case criticality accident.

Table 7. Results of Dose Calculations for Each Case

Case	Description	Bin	100 m Dose (millirem)	1000 m Dose (millirem)
1a	Step insertion by rod ejection or geometry change	Bare/Dry Solid	493	9.6
1b	Step insertion by water immersion	Moderated/reflected system	4.5	0.1
2a	Initial burst followed by longer critical period caused by geometry change or partial rod withdrawal	Bare/Dry Solid	63	1.2
2b	Initial burst followed by longer term pulsing reactor from water ingress	Moderated/reflected system	61	1.2

Estimation of Conservatism

A qualitative estimate of conservatism of the dose calculations is shown in Table 8. Several of the parameters are only mildly conservative. The source term is neutral, since the code used calculates a fission product inventory using the reactor core cross-section and fission yield. The atmospheric dispersion calculations are very conservative and are probably at least one order of magnitude than a more realistic (50%) weather event. All together the dose calculations would be considered moderately conservative.

Table 8. A Qualitative Estimate of Calculation Conservatism

Parameter	Method	How Conservative?
Number of Fissions	Historic data from actual criticality accidents	Slightly conservative (largest criticality accident for the category)
Release Fractions	Experiments to simulate worst case accidents for space fission systems	Slightly conservative (conditions contrived for some releases)
Source term	Calculated using Kilopower cross-sections and number of fissions	Neutral
Atmospheric Dispersion	Simple Gaussian dispersion for conservative weather conditions	Very conservative weather and release characteristics (release height)
Dose conversion factors	Standard ICRP values for inhalation (no immersion or shine)	ICRP values are neutral. No shine is slightly non-conservative

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